Quantification of Soil GHG Emissions, Advances and Challenges in Grassland Ecosystems

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1. Introduction

Those Annex I countries who have ratified the United Nations Framework Convention on Climate Change (UNFCCC) have an obligation to report anthropogenic greenhouse gas (GHG) emissions and removals every year. The National Greenhouse Gas Inventory reports multiple gases (including carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4), carbon monoxide (CO), nitrogen oxides, and non-methane volatile organic compound) from six sectors: Energy, Industrial processes, Solvent and other product use, Agriculture, Land Use Land-Use Change and Forestry (LULUCF), and Waste. Reported emissions and removals therefore need to be as accurate as possible. Using Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines and a good practice approach is a pragmatic means of building inventories that are consistent, comparable, complete, accurate, and transparent – and also a means of maintaining them in a manner that improves inventory quality over time (IPCC 2006).

The goal is to provide improved estimates of GHG emissions and carbon storage, and reduce uncertainty in national inventories in the face of increasing agricultural intensification and the likelihood of dangerous climatic change.

Thus, measurement of soil–atmosphere exchange of agricultural GHGs – N2O and CH4 fluxes – is a prerequisite for improving the accuracy of the GHG gas inventory and for assessing the viability of mitigation options. These measurements are also important in developing and verifying the empirical and process-based modelling approaches that provide emission estimates at farm-scale and beyond. The major difficulty in quantifying annual fluxes of N2O and CH4 at field scale is the high spatial and temporal variability. This variability is attributed to the dependency of microbial N2O and CH4 production and consumption processes on environmental controls such as substrate availability, redox potential, and temperature. Understanding the spatial variability of fluxes is therefore essential to better constrain the magnitude of the soil–atmosphere exchange of N2O and CH4, and to design statistically valid measurement programmes to determine flux rates from plot to regional levels. A simple and versatile in situ measurement technique is required to determine emissions with sufficient spatial and temporal resolution. Improved assessment of GHG emissions also requires techniques for accounting for random variation within farm units, and knowledge of factors that contribute in systematic variation among different farms and between seasons.

Under the UNFCCC, the IPCC also provides a simple methodology to calculate N2O emissions from agricultural soils including fertilisers, animal waste, and crop residues where N input in each component is multiplied by the relevant emission factor (EF). Beyond this IPCC methodology there are a number of possible approaches to produce improved estimates using empirical and process-based models (Saggar et al. 2009).

Measurements of GHGs are notoriously difficult as the fluxes tend to be low overall but highly variable in time and space. GHG emissions can vary significantly within the space of a few metres due to variations in soil properties and the fact that animal urine and dung are deposited as patches of high nitrogen (N) concentration. This variability presents a major challenge for estimating emissions on an area basis from point measurements using chambers. This means that for accurate assessment of N2O emissions from a soil, measurements need to cover a large area and a long time period.
This paper provides a synopsis of present knowledge of the quantification of GHGs in grassland ecosystems using the already published papers, monographs, and reports. The topics covered are: i) measurement techniques; ii) challenges in measuring GHG emissions; iii) use of measured emissions and removals for developing National GHG inventory NZ; and iv) improvements and advances in emissions estimates with special reference to New Zealand.

2. MEASURING GREENHOUSE GAS EMISSIONS FROM SOILS

A number of methods are used to measure rates of exchange of CH₄ and N₂O between the soil surface and the atmosphere. These techniques could be classified into two groups: Bottom-up and Top-down. The bottom-up approach includes simple, relatively inexpensive, easy to adopt and widely used enclosure methods commonly called chamber technique. The top-down approach involves micro-meteorological methods with various degrees of complexity (Eddy covariance, flux gradient, Eddy accumulation, and backward Lagrangian dispersion). Several reviews provide information and discussion on these approaches (Hutchinson and Livingston 2002; Rochette and Hutchinson 2005; Pattey et al. 2007; Denmead 2008; Rochette and Eriksen-Hamel 2008; Saggar et al. 2009; Parkin and Venterea 2010). Recently, deKlein and Harvey (2012) compiled N₂O chamber methodology guidelines with contributions from leading experts in Global Research Alliance (GRA) member countries. This document details the current state of knowledge of chamber techniques and provides guidelines and recommendations for their use. This bottom-up method involves sampling gaseous emissions close to the soil surface. Usually a sealable chamber or base is inserted into the soil and the rate of N₂O build up within the chamber is measured. Multiple chambers are required to account for the spatial variability of N₂O emissions. Figure 1 shows some examples of equipment used to measure N₂O emissions. While top-down methods have the advantage of achieving spatial and temporal integration of fluxes, they need to be able to detect smaller gas concentrations and are generally expensive to use.

![Figure 1. Examples of equipment used for N₂O measurements. (a) Bottom-up; manual gas sampling chamber, (b) Top-down; micrometeorological tower.](image_url)
Chamber technique allows us to study treatment effects as well as to carry out specific process studies. The shortcomings of chamber technique, as discussed by Butterbach-Bahl et al. (2013), are due to effects on environmental conditions, limited coverage of soil surfaces (usually <1 m²) to adequately address the spatial heterogeneity, and disturbance caused by chamber or collar insertion in the soil and the cutting of roots. Moreover, due to limited manpower, gas sampling strategy can result in high uncertainties as the key flux data may be missed.

In the last 25 years, the prediction of N₂O emissions using process-based agro-ecosystem models has emerged as a promising route to deal with these issues – primarily at the local scale – and to identify the effect of soil conditions and grazing regimes on emission rates (Saggar et al. 2007, 2009). Several detailed biochemical process-based models of N-gas emissions have been developed in recent years to provide site-specific and regional-scale estimates of N₂O emissions. Among these, DNDC (Denitrification-Decomposition) simulates carbon and nitrogen biogeochemical cycles occurring in agricultural systems. Originally developed as a tool to predict N₂O emissions from cropping systems, DNDC has since been expanded to include other ecosystems such as rice paddies, grazed pastures, forests, and wetlands, and the model accounts for land-use and land-management effects on N₂O emissions.

As a process-based model, DNDC is capable of predicting the soil fluxes of all three terrestrial greenhouse gases: N₂O, CO₂, and CH₄, as well as other important environmental and economic indicators such as crop production, ammonia (NH₃) volatilisation and nitrate (NO₃⁻) leaching. The DNDC model has been widely used internationally, including in the EU nitrogen biogeochemistry projects NOFRETETE and NitroEurope. Giltrap et al. (2009) produced an ample review of the researches undertaken on a wide range of land-use and land-management systems to improve and modify, test and verify, and apply the DNDC model to estimate soil-atmosphere exchange of N₂O, CH₄ and CO₂ from these systems.

Saggar et al. (2005) assessed the practicalities of implementing process-based modelling methods to quantify N₂O emissions. This was followed by an integrated experiment (Saggar et al. 2009), designed for model development with farm-scale validation to determine the level of agreement among emissions estimates obtained from chambers and micrometeorological measurements and a process-based model NZ-DNDC on an irrigated dairy-grazed pasture. Figure 3 shows the chamber and micrometeorological (Tuneable Diode Laser; TDL) measured and the DNDC modelled emissions. The model results tended to fit the chamber data better, with a high degree of model under-prediction compared with micrometeorological results. The continuous micrometeorological measurements are
typically more expensive and so cannot be widely adopted. However, they are useful to characterise the duration and frequency of emission episodes, and valuable for refinement and calibration of process-based model estimation.

![Figure 3. Measured and modelled $\text{N}_2\text{O}$ emissions (From Saggar et al. 2010).](image)

### 3. CHALLENGES IN EMISSION MEASUREMENTS

**Spatial variability:** Chambers are a comparatively inexpensive method, easy to adopt and handy, and for the last 40 years these have been most commonly used to measure $\text{N}_2\text{O}$ fluxes in the field. In this method gas samples are periodically taken from an enclosed area above the soil and the flux calculated from the increase in $\text{N}_2\text{O}$ concentration. However, $\text{N}_2\text{O}$ emissions tend to be highly right-skewed due to emissions hot spots formed by urine patches. This means many common statistical analysis techniques that assume a Normal distribution cannot be applied. In a recent study, Giltrap et al. (2014a), using 100 chambers divided into 4 blocks of 25 chambers in a dairy grazed pasture soil arranged in a $5 \times 5$ m grid, still reported a high variability in the sample mean. They concluded that improved understanding of the contribution of underlying soil properties such as soil moisture, pH, compaction, and N input to $\text{N}_2\text{O}$ emissions variability could enable the development of models to more accurate estimates of field scale emissions.

As emissions cannot be measured for individual farms, they are estimated using experimentally determined emission factors and fractions.

**Up-scaling:** There is also a need to estimate $\text{N}_2\text{O}$ emissions at regional, national, and global scales. In addition to the IPCC methodology, up-scaling models developed at field scale are one way to achieve this, but scaling over different time scales can be challenging. $\text{N}_2\text{O}$ budgets to national and regional scales remain an unresolved challenge, with current national estimates still highly uncertain.

### 4. DEVELOPING NATIONAL GREENHOUSE GAS INVENTORY

The international political response to climate change began with the adoption of the UNFCCC in 1992 with the objective of achieving stabilisation of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system and ensure food production is not threatened. By June 2013, 195 Parties and has ratified UNFCCC.
Under the UNFCCC, Annex I Parties are required to monitor trends in anthropogenic GHG emissions and submit the Inventory to the UNFCCC Secretariat each year. Each inventory is reviewed to ensure emissions and removals are estimated accurately and transparently (UNFCCC 2010). The Inventory Methodological guidelines for reporting emissions and removals have been developed by the Intergovernmental Panel on Climate Change (IPCC), which was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in response to climate change.


The IPCC guidelines have various levels of complexity based on the ability of a country to gather data and carry out improvements to its National Inventory, and the importance of the GHG source category. These guidelines encourage countries to improve the estimation of their emissions by developing emission factors, fractions, and parameters through research and the use of country-specific information.

The most basic level is Tier 1, where the default factors (emission factors and fractions) and proportions are applied to basic data, such as population numbers, to estimate GHG emissions from each sector. Tier 1 uses assumptions on production that are incorporated into default factors and population proportions for management systems. Tier 2 uses a more complex methodology that can be applied if disaggregated population data and production data for a country are available. The bases of this Tier 2 methodology for livestock emissions are the estimation of the energy requirements for cattle and subsequently the required dry matter intake. As CH$_4$ and N$_2$O emissions are related to the dry matter intake of an animal, these emissions can therefore be determined from the estimated dry matter intake. Tier 3 requires the countries to develop their own country-specific models to estimate emissions from an anthropogenic source. The tiered structure ensures estimates are calculated at a detailed level that can be aggregated up to a common minimum level of detail for comparison with all other reporting countries.

New Zealand has developed its own Tier 2 methodology (Inventory model) and uses a detailed livestock population characterisation and livestock productivity data to determine the energy requirements of dairy cattle, beef cattle, sheep, and deer, and subsequently the methane and N$_2$O and CH$_4$ from each species (Clark et al. 2003). The population model developed to conform to the IPCC good practice guidelines, using industry knowledge and assumptions, has been described in Clark (2008) and is constantly under improvement. It takes into account the changing productivity of cattle, sheep, and deer and provides a more accurate estimate of emission from New Zealand’s key animal species compared with fixed default emission factors. A detailed methodology report for calculating New Zealand agricultural GHG emissions (Pickering and Simon 2013) is available on the New Zealand Ministry for Primary Industries website: [http://www.mpi.govt.nz/news-resources/publications.aspx](http://www.mpi.govt.nz/news-resources/publications.aspx)

Nitrogen is added to the soil through the application of inorganic fertilisers, animal wastes, and crop residues, biological processes such as nitrogen fixation, mineralisation and atmospheric deposition, and the leaching of inorganic nitrogen and subsequent denitrification.

The major sources of N$_2$O emission in grasslands are N fertilisers, animal urine and dung, manures, farm dairy effluents and slurry, biological N fixation, and the atmospheric deposition of N. Table 1 shows the amounts of sources of N in New Zealand grazed pasture soils and gaseous or leaching N loss mechanisms.
Table 1. Nitrogen sources and forms of loss in grazed pasture systems.

<table>
<thead>
<tr>
<th>N source</th>
<th>Annual N (Gg N)</th>
<th>Direct Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biological N₂ Fixation</td>
<td>700 to 1,000</td>
<td>N₂O, NO, N₂</td>
</tr>
<tr>
<td>Animal excreta</td>
<td>1,589</td>
<td>NH₃, N₂O, NO, N₂, NO₃</td>
</tr>
<tr>
<td>Fertiliser</td>
<td>360</td>
<td>NH₃, N₂O, NO, N₂, NO₃</td>
</tr>
<tr>
<td>Effluents, slurry and manures</td>
<td>7</td>
<td>NH₃, N₂O, NO, N₂, NO₃</td>
</tr>
<tr>
<td>Atmospheric deposition</td>
<td>~1</td>
<td>NH₃, N₂O, NO, N₂, NO₃</td>
</tr>
</tbody>
</table>

An example (below) shows emissions from agricultural soils that are reported in the agricultural section of the New Zealand National inventory consisting of N₂O emissions from direct and indirect pathways as a result of the application of nitrogen to the soil. The agricultural soils category is the source of most N₂O emissions in New Zealand (MfE 2005). This category comprises of three sub-categories:

- Direct N₂O emissions from animal production (the pasture range and paddock AWMS) – EF₃PR&P
- Direct emissions from agricultural soils as a result of adding fertiliser N, animal waste, input from crop residues and sewage sludge – EF₁
- Indirect emissions N₂O from N lost from the field as NOₓ or NH₃ – EF₄, EF₅, Frac_GASM, Frac_GASP, Frac_Leach

The two main inputs in New Zealand are from N fertiliser and excreta-N deposited during animal grazing.

Figure 4. Flow chart depicting direct and indirect sources of N₂O from fertiliser usage in New Zealand agriculture (from Pickering and Wear 2013).
The amount of N excreted ($N_{ex}$) is determined for each species by subtracting the N retained in the live weight gain and milk from N intake (kg DM intake determined from ME requirements × N in diet). The $N_{ex}$ is calculated based on same animal intake values used for calculating CH$_4$ for different animal species to ensure the same base values are used for both CH$_4$ and N$_2$O. This $N_{ex}$ is then split into N from urine and N from faeces. All sheep, deer, and non-dairy cattle excreta are allocated to EF$_{3\ R&P}$; for dairy cattle, 95% of the excreta are allocated to EF$_{3\ R&P}$ and 5% to anaerobic lagoon. A time series of $N_{ex}$ shows an increase over time caused by increases in production per animal. To ensure consistency with good practice the entire time series are recalculated to a country-specific EF with any changes of EF.

Figure 5. Flow chart of the current IPCC national N$_2$O inventory methodology for pastoral agriculture in NZ (from Pickering and Wear 2013).

5. IMPROVEMENTS AND ADVANCES IN N$_2$O EMISSIONS ESTIMATES –THE NEW ZEALAND EXPERIENCE

A fundamental requirement for reporting of GHG emissions and carbon stocks is the robustness of estimates in the annual inventory. This includes quantifying what is stored where, understanding the complex processes that govern fluxes between terrestrial environments and the atmosphere, and how land use and climate affect sinks and emissions.

Over the years New Zealand has made significant improvements in its N$_2$O emissions inventory by developing New Zealand-specific emission factors through the results obtained from a number of field experiments conducted to represent New Zealand soil, environmental and management conditions, reviewing of national and international published and unpublished data. New Zealand also makes use of activity data from Statistics New Zealand’s annual Agricultural Production Survey (APS) and census, and from New Zealand Dairy Statistics, Beef and Lamb New Zealand, and slaughter statistics collected by the Ministry for Primary Industries (MPI).

The New Zealand developed improved EFs values currently used to calculate N$_2$O emissions Inventory and given in Figure 5 are: i) $\text{Frac}_{\text{GASM}}$, ii) $\text{Frac}_{\text{GASF}}$, iii) $\text{Frac}_{\text{Leach}}$, iv) EF$_{1}$, v) EF$_{3\ R&P}$, vi) EF$_{3\ R&P} \& \text{dung}$, vii) EF$_{4}$, and viii) EF$_{5}$, and has
also incorporated the effects of using the nitrification inhibitor DCD assuming a reduction of 67% in direct $\text{N}_2\text{O}$ emissions from animal total excretal–N when DCD is applied (MfE 2012) which also assumes a 53% reduction in $\text{NO}_3^{-}$ leaching following DCD application based on a review by Clough et al. (2008).

For inventory purposes, emissions reductions from the use of urease inhibitors have recently been quantified and specific $\text{Frac}_{\text{GASF}}^{\text{F}_{\text{NUI}}}$ values developed (Saggar et al. 2013). Saggar et al. (2013) recommend that, based on an average ammonia emission reduction value derived from a number of New Zealand studies, using soil with low and high organic C levels and urea application rates of 50–150 kg N ha$^{-1}$ the $\text{Frac}_{\text{GASF}}$ value for UI-treated urea be changed from 0.1 to 0.055.

More recently, the current estimate of emissions from the excreta of livestock grazing on hill country were recognised as a possible source of overestimation of $\text{N}_2\text{O}$ emissions in New Zealand. Giltrap et al. (2014b) investigated a potential new inventory methodology for calculating $\text{N}_2\text{O}$ emissions from sheep, beef, and dairy by taking into account the effects of hill country slopes on emissions and assessing the impact of these effects on inventory emissions between 1990 and 2012. This report has been submitted to MPI last month. When adopted and included into the Inventory, these new estimates would provide more accurate $\text{N}_2\text{O}$ inventory data for direct $\text{N}_2\text{O}$ emissions estimates from sheep, beef and deer and allow for further improvements by including the measured $\text{N}_2\text{O}$ EFs from steeper slopes. The IPCC inventory guidelines encourage countries to develop country-specific emission factors, fractions, and parameters through research and to improve emissions estimates. The Inventory improvements made following the IPCC 2006 guidelines and a good practice approach are practical means of building inventories that are consistent, comparable, complete, accurate, and transparent. Such an approach allows inventory quality to improve over time. To ensure consistency with good practice the entire time series should be recalculated following changes in any of the EFs to a country-specific value.

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7. REFERENCES


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